

Variation of Molecular Cloud Properties across the Spiral Arm in M 51

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Abstract

We present the results of high-resolution ^{13}CO ($J = 1-0$) mapping observations with the NRO 45m telescope of the area toward the southern bright arm region of M 51, including the galactic center, in order to study the physical conditions of the molecular clouds in the arm and the interarm. The obtained map shows the central depression of the ^{13}CO ($J = 1-0$) emission, the circumnuclear ring (radius $\sim 10'' - 20''$), and the spiral arm structure. The arm-to-interarm ratio of the ^{13}CO ($J = 1-0$) integrated intensity is 2 – 4. We also have found a feature different from that found in the ^{12}CO results. For example, the ^{13}CO distribution shows a depression in part of the spiral arm. The $^{12}\text{CO}/^{13}\text{CO}$ ratio spatially varies, and shows high values (~ 20) for the interarm and the central region, but low values (~ 10) for the arm. Their values indicate that there is a denser gas in the spiral arm than in the interarm.

The distribution of the ^{13}CO shows a better correspondence with that of the $\text{H}\alpha$ emission than with the ^{12}CO in the disk region, except for the central region. We found that the ^{13}CO emission is located on the downstream side of the ^{12}CO arm, namely there is an offset between the ^{12}CO and the ^{13}CO as well as the $\text{H}\alpha$ emission. This suggests that there is a time delay between the accumulation of gas caused by the density wave and dense gas formation, accordingly star formation. This time delay is estimated to be $\sim 10^7$ yr based on the assumption of galactic rotation derived by the rotation curve and the pattern speed of the M 51 spiral pattern. It is similar to the growth timescale of a gravitational instability in the spiral arm of M 51, suggesting that the gravitational instability plays an important role for dense gas formation.

Key words: galaxies: individual(M 51)— galaxies: ISM — galaxies: spiral

1. Introduction

One of the most important aims of research is to develop an understanding of the formation mechanism of dense molecular gas in a study of star formation in galaxies, because there is a clear correlation between the amount of dense gas and star formation, namely, stars are born in dense gas clouds. On the other hand, spiral structures, which are a striking feature of galaxies, are thought to have a correlation with dense gas formation and/or star formation because the spiral structures are due to density waves that are expected to accumulate or compress the molecular gas.

Recent observational studies at millimeter and submillimeter wavelengths have revealed that there exists molecular gas with high temperature and/or high density in external galaxies, especially at galactic centers. These molecular gas properties are greatly different from those of our Galaxy, such as Giant Molecular Clouds (GMCs) in the Galactic disk. However, only a few attempts to understand the properties of molecular gas have so far been made in a galactic disk that is on and between the spiral arms (000 [cite]cite.key-GB93aGarcia-Burillo et al.(1993a)a; 000 [cite]cite.key-Kuno95Kuno et al.(1995)), because emission is weaker in the disks than in the galactic centers.

Because ^{13}CO ($J = 1-0$) emission is relatively stronger than other molecular line emissions, except for ^{12}CO ($J = 1-0$), many studies have been made of our Galaxy and external galaxies. ^{13}CO is optically thin and a tracer of denser gas ($\sim 10^{3-4} \text{ cm}^{-3}$) than that traced by $^{12}\text{CO}(J = 1-0)$ ($\sim 10^{2-3} \text{ cm}^{-3}$), which is optically thick and surrounds dense molecular gas. Also, ^{12}CO is a good tracer of molecular gas mass through the conversion factor from the integrated intensity of ^{12}CO to N_{H_2} (column density of H_2). Consequently, the ratio of $^{12}\text{CO}(J = 1-0)/^{13}\text{CO}(J = 1-0)$ can be used as an indicator of gas density with a low or moderate temperature and normal metallicity. The $^{12}\text{CO}(J = 1-0)/^{13}\text{CO}(J = 1-0)$ ratios are smaller than ~ 10 for the Galactic plane (000 [cite]cite.key-Sol79Solomon et al.(1979); 000 [cite]cite.key-Pol88Polk et al.(1988)), and for the disk of galaxies, e.g. NGC 891 (000 [cite]cite.key-Saka97Sakamoto et al.(1997)). On the other hand, the starburst galaxies have higher ratios (000 [cite]cite.key-Aal95Aalto et al.(1995); 000 [cite]cite.key-Kiku98Kikumoto et al. (1998)). We must note that the high ratio is seen in the high latitude clouds of our Galaxy which are diffuse cold gas (000 [cite]cite.key-Pol88Polk et al.(1988)).

To study the nature of molecular clouds in the central region, the spiral arm and the interarm of galaxies and to consider the effect of spiral arms on dense gas formation and star formation, we present the results of observations using $^{13}\text{CO}(J = 1-0)$ and $\text{H}\alpha$ emission toward the inner disk of the nearby spiral galaxy M 51. M 51 is a famous grand-design spiral galaxy and has been investigated by numerous observations at various wavelengths, e.g., optical, infrared, radio, and so on. This galaxy shows two beautiful spiral arms, and kinematic indications of density waves also have been found within it. We also note that an oval/bar potential is seen

Table 1. Adopted parameters of M 51.

Parameter	Value
Center position (2000.0) ^a	13 ^h 29 ^m 52.71 ^s 47°11′42.6″
Morphological type ^b	Sbc
Systemic Velocity ^c	463 km s ⁻¹
Distance ^d	9.6 Mpc
Position angle ^c	170°
Inclination ^c	20°

a: [te\[cite.key-TH94Turner and Ho\(1994\)\]\(\[cite\]cite.key-TH94Turner and Ho\(1994\)\)](#).

b: [te\[cite.key-dV91de Vaucouleurs et al.\(1991\)\]\(\[cite\]cite.key-dV91de Vaucouleurs et al.\(1991\)\)](#).

c: [te\[cite.key-Tully74Tully\(1974\)\]\(\[cite\]cite.key-Tully74Tully\(1974\)\)](#).

d: [te\[cite.key-ST74Sandage and Tammann\(1974\)\]\(\[cite\]cite.key-ST74Sandage and Tammann\(1974\)\)](#).

in the central region of M 51 which has an Active Galactic Nucleus (AGN: (000 [\[cite\]cite.key-Tera98Terashima et al.\(1998\)](#)). The parameters of M 51 are summarized in table 1.

2. Observations

2.1. ¹³CO observed with the 45m Telescope at Nobeyama Radio Observatory (NRO)

We performed observations of ¹³CO($J = 1-0$) emissions toward the south bright arm region of M 51, including the galactic center, between 1994 December and 1995 March with the 45-m telescope at Nobeyama Radio Observatory (NRO). The full width at a half-power beam (FWHP) was 17″ at a rest frequency of ¹³CO($J = 1-0$) (110.2 GHz), which corresponds to 782 pc at a distance from M 51 of 9.6 Mpc. The size of the observed region is 100″ × 120″ (4.6 kpc × 5.5 kpc) and the observing grid has an 11″ spacing (see figure 1). The absolute pointing accuracy was checked every hour using a SiO maser source, and was found to be better than 5″ (peak value) throughout the observations. The main beam efficiency was $\eta_{\text{mb}} = 0.38$ at 110 GHz. We used the 2 × 2 SIS focal-plane array receiver, which can simultaneously observe four positions separated on the sky by 34″ each (000 [\[cite\]cite.key-Suna95Sunada et al.\(1995\)](#)). The typical system noise temperatures, including atmospheric effects and antenna ohmic losses, were about 400 K. The 2048-channel wide-band acousto-optical spectrometers (AOS) were used as receiver backends. The frequency resolution and the channel spacing were 250 kHz and 125 kHz, respectively, and the velocity resolution was 0.68 km s⁻¹ at 110 GHz. The total bandwidth was 250 MHz, corresponding to 680 km s⁻¹. The integration times of each observing point were 80 – 100 minutes in most of the observed region, except for some of the points. Because those exceptional points were very short (~ 5 min), we did not use them to make the total integrated map (see subsection 3.1).

2.2. *H α observed with 65cm Telescope at Gunma Astronomical Observatory (GAO)*

2.2.1. *Imaging observation*

A H α image of M 51 was obtained with the 65cm telescope at the Gunma Astronomical observatory (GAO) between 2000 December 29 and 2001 January 11. Although the best seeing was 2".5, most of the images used for this study had seeing values of between 3" and 3".5, which were good enough for comparison with the CO data taken with the NRO-45m telescope. A CCD camera assembled by Apogee was attached to the telescope. Installed in this camera was a SITe CCD chip of 1024 *times* 1024 pixels. The pixel size of this chip, 24 μ m, corresponds to 0".6 in the sky and so this camera has a field of view (FOV) of 10'.6 square. This FOV was wide enough not only to cover the entire galaxy pair (M 51 and NGC 5195), but to provide an area for a sky-level evaluation. This camera was cooled down to -40°C with a water cycle. The temperature was stable within 1°C each night.

Two narrow-band filters were used with a nominal bandpass of 20 \AA centered at 6584 \AA , and 6620 \AA , corresponding to the wavelength of H α and continuum light, respectively. These filters were designed to have a boxy-shaped transmittance curve, so that the nebular emission could be detected evenly over the galaxy allowing for the rotation of the galaxy. We must note that the redshift of M 51 puts H α at 6573 \AA . This suggests that the edge of these filters have a much higher sensitivity to the receding side than the approaching side. Because the observed region of ^{13}CO corresponds to the receding side, we can say that there was little effect on the obtained H α distribution compared with the ^{13}CO map.

We recognize that images from this camera were subject to the so-called memory effect: an image has traces of stars that appeared in preceding exposures. Mainly to avoid this effect, we drifted the telescope by approximately 30" for each exposure. Because of angular size of the bulge of M 51 is much larger than this, we estimated that the memory effect due to the bulge was less than the order of 3% of the H α nebular emission, though the effect would be significantly suppressed by the drift of the telescope and the clipping algorithm in the image reduction.

The exposure time was set at 10 min for all exposures. We restricted ourselves to using 6 images for each filter with good image quality (less atmospheric extinction, better seeing, and, more importantly, less contamination from the memory effect). This gives 60 minutes exposure for each filter in total.

2.2.2. *Image reduction*

Reduction was carried out with IRAF in the standard manner. Dark frames were combined. The mean level of the dark current has a monotonic decrease due to the memory effect, since it was obtained after illuminating the twilight sky to take flat-field images. This decrease introduced some ambiguity in the dark-subtraction. However, this ambiguity in the dark current was almost flat across the FOV, and we assume that local patterns (i.e. individual H II

regions) of the nebular emission were not badly corrupted. Flat-fielding was made with combined twilight sky-flat images. The flat-field images are not flat by an order of 5% due to inhomogeneous transmittance across the filter. It is not easy at all to remove this inhomogeneity, and although the final image has a residual of a flat-fielding correction, it is of a much lower level ($\sim 10\%$) than that of the $H\alpha$ emission of typical H II regions. Again, this residual is global and would not corrupt the small scale patterns of $H\alpha$ emission discussed in this paper.

Hampered by ambiguities in the dark-subtraction and the flat-fielding, we made sky-subtraction with a constant value evaluated in the area where it is virtually free from light from the galaxies (M 51 and NGC 5195) in the broad-band images. Scaled by the mean flux of 8 stars appearing in images, 6 images of each filter were combined after positional registration. The scaling has typically 5 – 10% ambiguity due to the poor photon statistics of the stars in the narrow-band images. The positional registration is acceptable within $0''.2$. Continuum light was subtracted from the $H\alpha$ image, again, scaled by the 8 stellar fluxes which appeared in both images. The stellar fluxes are consistent only within 5%.

The $H\alpha$ emission in the bright H II regions has a signal-to-noise ratio of better than 10, if the standard deviation in the sky area is adopted for the noise source. Taking into account the ambiguity in the subtraction and the scaling, we estimate that the $H\alpha$ emission may have 20% ambiguity, but the local patterns (i.e., smaller than the flat-field inhomogeneity) would have a much better confidence level.

Figure 1 shows the resultant $H\alpha$ image of M 51. No efforts were made to correct the extinction in the parent galaxy. This $H\alpha$ emission was largely consistent with the previous studies. A $H\alpha$ image of M 51 was first carefully examined by [Ken89b](#) ([Ken89b](#)), and several studies followed ([Rand90](#) and [Kulkarni\(1990\)](#); [Thilk00](#) ([Thilker et al.\(2000\)](#)). Although quantitative a comparison via detailed photometry of individual H II regions is not our aim, the remarkable similarity of the emission of bright and faint H II regions would support the validity of our observations and data reduction. We note that the paucity of $H\alpha$ emission in the center of NGC 5195 is consistent with the spectroscopic study ([Ho95](#) ([Ho et al.\(1995\)](#))), giving additional support to our reduction.

It should also be added that the 3 stars in the observed region have been used to do *absolute* astrometry. The accuracy has been estimated to a few arcsecs, which is enough to compare with the ^{12}CO and ^{13}CO data.

3. Results and Discussion

3.1. Global Distribution of ^{13}CO Emission

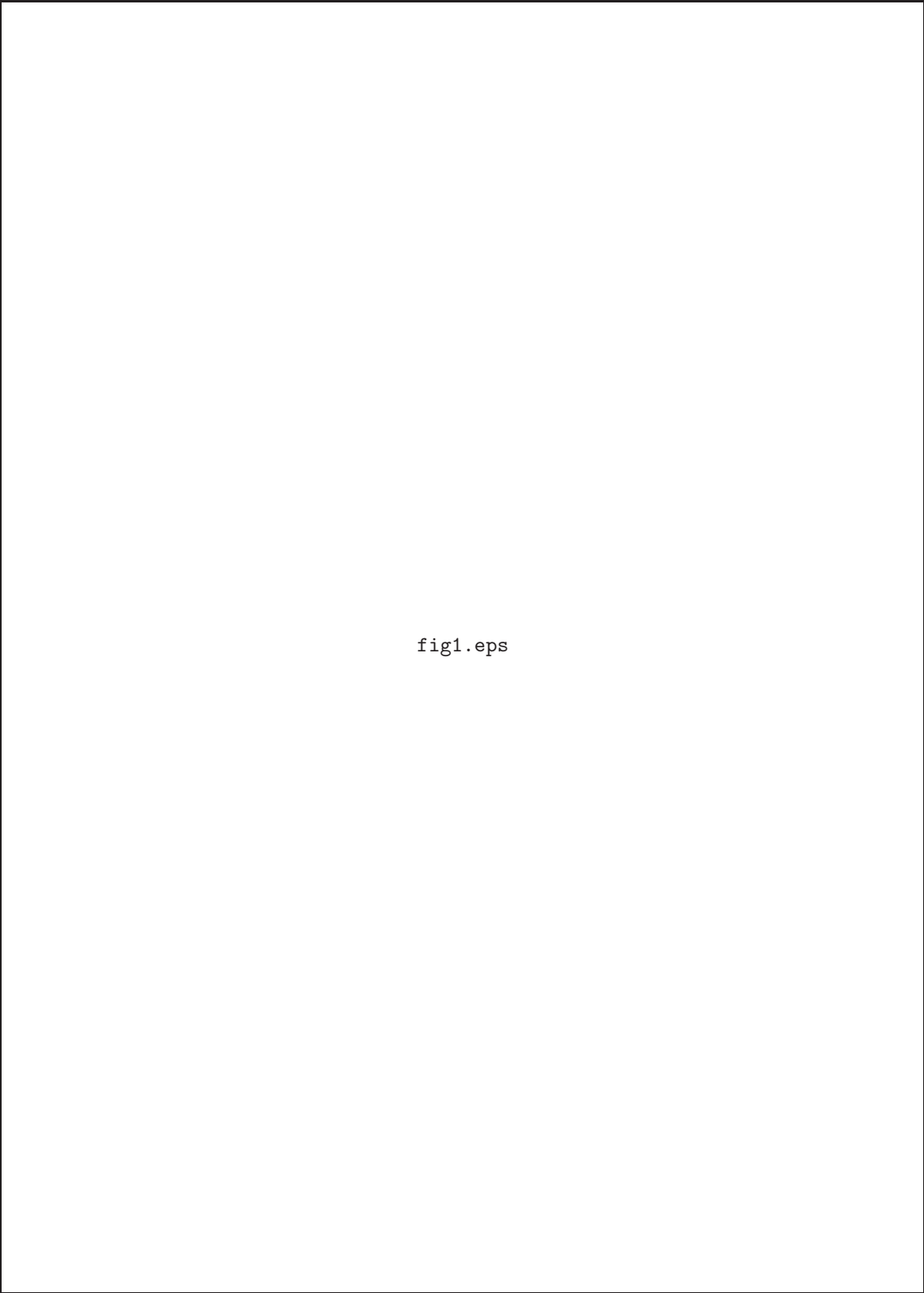


fig1.eps

Fig. 1. $H\alpha$ narrow-band image of M 51(NGC 5194). The observed points of ^{13}CO are indicated by the crosses in the figure. The observing grid uses $11''$ spacing.

3.1.1. Spectral line profile

Figure 2 shows a line-profile map of the ^{13}CO emission in the observed region. As can be seen in this figure, we detected emission in most of the observed region. However, because the emission for a part of the south, west, and north-east regions had poor signal-to-noise, we didn't use these data to make an integrated intensity map. It should be noted that the emission in the central region of M 51 is very weak, though we found strong emissions surrounding the central region, namely the bar-end or the beginning of the spiral arms. In particular, the west side of the bar-end shows very strong emission.

Figure 2 also shows the detection of emission from the interarm as well as strong emission along the spiral arm. Figure 2 indicates that a typical peak T_{mb} of the emission in the arm is ~ 200 mK and that the west bar-end has very strong emission with T_{mb} higher than 300 mK. On the other hand, the peak T_{mb} in the interarm is ~ 100 mK. This means that T_{mb} in the arm is higher than that in the interarm by a factor of 2–3. We were also able to find a larger velocity dispersion in the arm, $30 - 50 \text{ km s}^{-1}$, than that in the interarm, $\sim 20 \text{ km s}^{-1}$. The larger velocity width in the arm than in the interarm is consistent with previous studies of the ^{12}CO observations, and can be explained by the streaming motion at spiral arms caused by density wave shock (000 [cite]cite.key-Kuno97Kuno & Nakai(1997); 000 [cite]cite.key-GB93aGarcia-Burillo et al.(1993a)a).

3.1.2. Spiral structure

The spatial structures of the ^{13}CO emission are clearly revealed in the total integrated intensity map (figure 3). Figures 3a, b, and c show the total integrated map of ^{13}CO emission superposed on a color scale of the ^{13}CO emission, itself, the ^{12}CO emission, and the $\text{H}\alpha$ emission, respectively. Figure 3a shows a depression in the $^{13}\text{CO}(J = 1-0)$ emission in the central region of M 51. The distribution also has strong concentrations in both bar-ends, especially on the west side. Due to the central depression, we find a ring-like structure surrounding the central region. This depression was pointed out by previous interferometric observations of M 51 (000 [cite]cite.key-Matsu98Matsushita et al.(1998)). From figure 2, we have estimated the arm-to-interarm ratio using the 13 and 8 line profiles of the arm and the interarm, respectively. We add that the profiles which we cannot distinguish between the arm and the interarm due to the location at the edge of the arm have been excluded. Their intensities are $4.2 - 12.6$ and $1.3 - 3.6 \text{ K km s}^{-1}$ for the arm and the interarm, respectively. The intensities in the arm significantly vary while in principle they are increasing with a smaller radius. On the other hand, we can not see the large variation in the interarm, though a slightly larger intensity is seen near the beginning of the spiral arm. Comparing the profiles in the arm with the near ones in the interarm, we estimate the arm-to-interarm ratio of the total integrated intensity of the $^{13}\text{CO}(J = 1-0)$, to be 2 – 4. The high ratio can be seen at the beginning of the arm or the smaller radius due to the high intensity seen there. We can also see the arm-to-interarm ratio in the

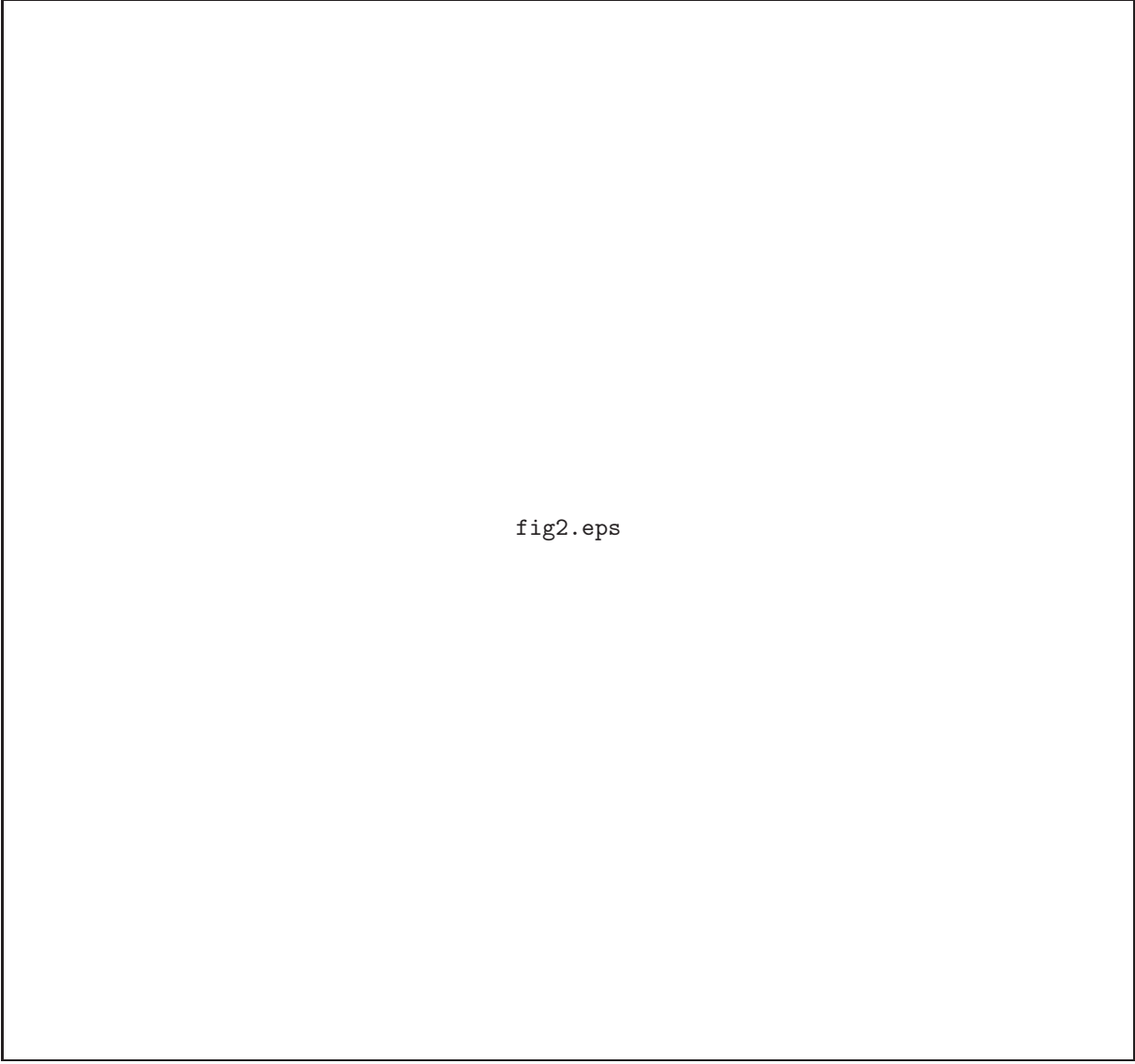


fig2.eps

Fig. 2. Line-profile map of the ^{13}CO emission spectra with NRO-45m. The velocity resolution of the spectra is 5 km s^{-1} . The x and y axes of the map are the right ascension and the declination in units of arcsec and (0, 0) in the figure is the galactic center. The vertical and horizontal axes of each spectrum are T_{mb} (K) from 0 to 0.4 K and V_{LSR} (km s^{-1}) from 300 to 600 km s^{-1} , respectively.

azimuthal distribution of the ^{13}CO in the following figure (figure 10), showing the same ratio as that estimated here. This indicates that the ratio virtually depends on the intensities in the arm. Although the ratio seems to be similar to the global ratio of the ^{12}CO ($J = 1-0$) (000 [cite]cite.key-Kuno95Kuno et al.(1995)), the arm-to-interarm ratio of the ^{12}CO decreases with a smaller radius toward the galactic center, and consequently the arm-to-interarm ratio of the ^{13}CO in the observed region is higher than that of the ^{12}CO . We note that the ratio varies spatially in the spiral arm, showing a high ratio at a smaller radius, or rather near the beginning of the spiral arm, as mentioned above.

These morphological structures are globally in agreement with those of the ^{12}CO emission (figure 3b). However, a close look at the distributions of the ^{12}CO and the ^{13}CO will reveal the difference between them. First, we can see that there is a depression on the ^{13}CO spiral arm located at (R.A., Decl.) = ($13^{\text{h}}29^{\text{m}}51^{\text{s}}$, $47^{\circ}11'00''$), unlike in the ^{12}CO arm. In other words, the extension of the spiral arm of the ^{13}CO from the bar-end is shorter than that of the ^{12}CO . Next, in figure 3b we find an offset between the ^{12}CO and the ^{13}CO arms. This offset seems to be obvious, especially at the beginning of the spiral arm and the peak at (R.A., Decl.) = ($13^{\text{h}}29^{\text{m}}57^{\text{s}}$, $47^{\circ}10'50''$). Taking account of the motion of gas in the frame of galactic rotation on the assumption of the existence of a trailing arm, the ^{13}CO arm is located on the downstream side of the ^{12}CO arm. On the other hand, in figure 3c which is the ^{13}CO map superposed on the $\text{H}\alpha$ emission contour, we can see that the depression on the ^{13}CO arm is located in a region where the $\text{H}\alpha$ emission is not detected. Also, the $\text{H}\alpha$ arm is located on the downstream side of the ^{12}CO arm and the ^{13}CO arm is located along and closer to the $\text{H}\alpha$ arm than the ^{12}CO arm. These observations indicate that the ^{13}CO arm shows a closer correspondence to the $\text{H}\alpha$ emission than the ^{12}CO emission in the arm region. Figure 4 helps to clarify these features. This figure is an $R - \theta$ plot of ^{13}CO emission superposed on ^{12}CO and $\text{H}\alpha$ emissions, where R and θ are the distance from the center and the azimuthal angle for a face-on view, respectively. These figures have a range at from $R = 30''$ to $100''$, covering the spiral arm and not including the central region. It makes the existence of the spiral arm clearer. In the figures, we can see the depressions both on the ^{13}CO and the $\text{H}\alpha$ spiral arms at $R = 50''$ while there is no prominent depression on the ^{12}CO arm. We can also see that the ^{13}CO arm shows good agreement with the $\text{H}\alpha$ emission at $R = 30'' - 50''$ and $70'' - 80''$ while they show offsets from the ^{12}CO arm, or rather, they are located on the downstream side of the ^{12}CO arm. On the other hand, at $R = 60'' - 70''$, the ^{13}CO has an offset from both the ^{12}CO and the $\text{H}\alpha$. This prompts us to ask what is the difference between them? The $\text{H}\alpha$ emission at $R = 60'' - 70''$ is located at R.A. = $13^{\text{h}}29^{\text{m}}52^{\text{s}}$ and Decl. = $47^{\circ}10'40''$. It is clear that the distance of this $\text{H}\alpha$ emission from the dust lane and the ^{12}CO arm is more than twice the distance compared with the other $\text{H}\alpha$ emission (cf. figure3 in 000 [cite]cite.key-Rand92Rand et al.(1992)). Therefore, we can say that this region is not located on the spiral arm, or rather that it has already escaped from the arm. This exceptional region is discussed further in subsection 3.4. Therefore, we can say that

the distribution of ^{13}CO is more similar to $\text{H}\alpha$ than is the ^{12}CO on the spiral arm, except for a part of the arm. We conclude that both the ^{13}CO and the $\text{H}\alpha$ structures are located on the downstream side of the ^{12}CO structure.

3.1.3. Radial distribution

Figure 5 shows the radial distribution of the ^{13}CO emission, along with those of the ^{12}CO emission and the $\text{H}\alpha$ emission. This figure indicates the central depression and the ring-like structure of the ^{13}CO emission at a radius of $20'' - 30''$, corresponding to $0.9 - 1.4$ kpc. This ring-like structure reflects the central depression and the concentrations at the bar-ends, namely the beginnings of the spiral arm. This ring-like structure is very different from the distribution of the ^{12}CO , which gradually decreases toward the outside. Also, the ^{13}CO emission shows a rise at a radius of $55''$, which is coincident with the location of the spiral arm, while the ^{12}CO gradually decreases toward the outside of the galactic disk. These structures of ^{13}CO are in excellent correspondence with those of the $\text{H}\alpha$ emission, except for the galactic center. On the other hand, the radial distribution of the ^{12}CO emission is different from that of the $\text{H}\alpha$ emission.

The previous studies for the kinematics of M 51 reported the positions of the resonances. These studies give the positions of the Inner Lindblad Resonance (ILR), which range from $20''$ to $30''$, and that of the 4/1 resonance of $50'' - 60''$ (000 [cite]cite.key-Tully74Tully(1974); 000 [cite]cite.key-GB93bGarcia-Burillo et al.(1993b)b;000 [cite]cite.key-Aal99Aalto et al.(1999)). In the radial distribution shown in figure 5, we find two peaks at radii of $20''$ and $50''$, as mentioned above. We suggest that the inner ring corresponds to the ILR. Also, the outer peak is located on the radii of the 4/1 resonance. The ^{12}CO shows only a gradual decrease toward an outside, and does not show peak structures at the radii of the ILR and the 4/1 resonance.

3.2. $^{12}\text{CO}/^{13}\text{CO}$ Ratio; Molecular Cloud Properties

In figure 5, the radial distribution of the ratio of the ^{12}CO -to- ^{13}CO integrated intensities ($=R_{12/13}$) is also shown along with those of the ^{12}CO , ^{13}CO , and $\text{H}\alpha$ emissions. This figure indicates that the ratio has a range from 5 to 20, and that the central region shows a high ratio of ≥ 20 . This high ratio in the central region is due to the depression of ^{13}CO in the central region. Although the radial distribution of the $R_{12/13}$ gradually decreases with the radius, there is a slight increase between the inner ring of the ^{13}CO and the outer ring or the spiral arm. This suggests the possibility that the $R_{12/13}$ is high between the ring and the spiral arm, namely, in the interarm.

The spatial distribution of $R_{12/13}$ is clearer in figure 6 and figure 7, which are the superposed color and grey scale images of the ratio on the $\text{H}\alpha$ emission contour. As can be seen in these figures, $R_{12/13}$ is found to vary spatially. These diagrams indicate that the low $R_{12/13}$ of typically ~ 10 can be seen at the position of the spiral arm, except for a part of the region, and high $R_{12/13}$, ≥ 20 , at the positions of most of the interarm and the central regions. We must also

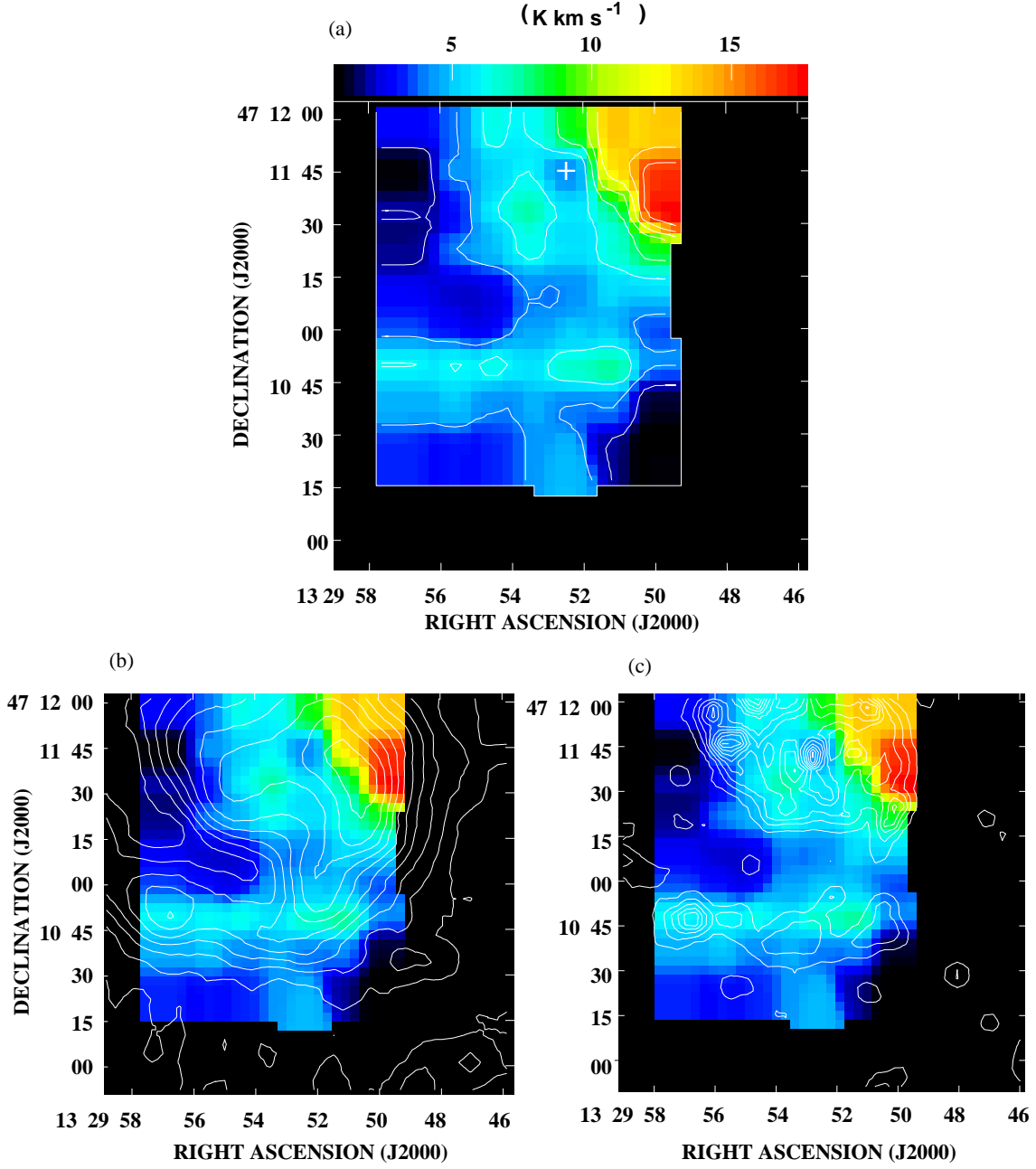


Fig. 3. (a) Total integrated intensity map of ^{13}CO emission obtained with NRO-45m. The contour interval and the lowest contour is 2 K km s^{-1} , corresponding to 2σ . The cross indicates the galactic center of M 51. (b) superposition of (a) on the ^{12}CO emission map (contour; 000 [cite]cite.key-Naka94Nakai et al.(1994)). The contour interval and the lowest contour is 10 K km s^{-1} . (c) superposition of (a) on the $\text{H}\alpha$ emission map convolved to the $4''$ beam (contour). The contour interval is 1 in the lowest contour units.

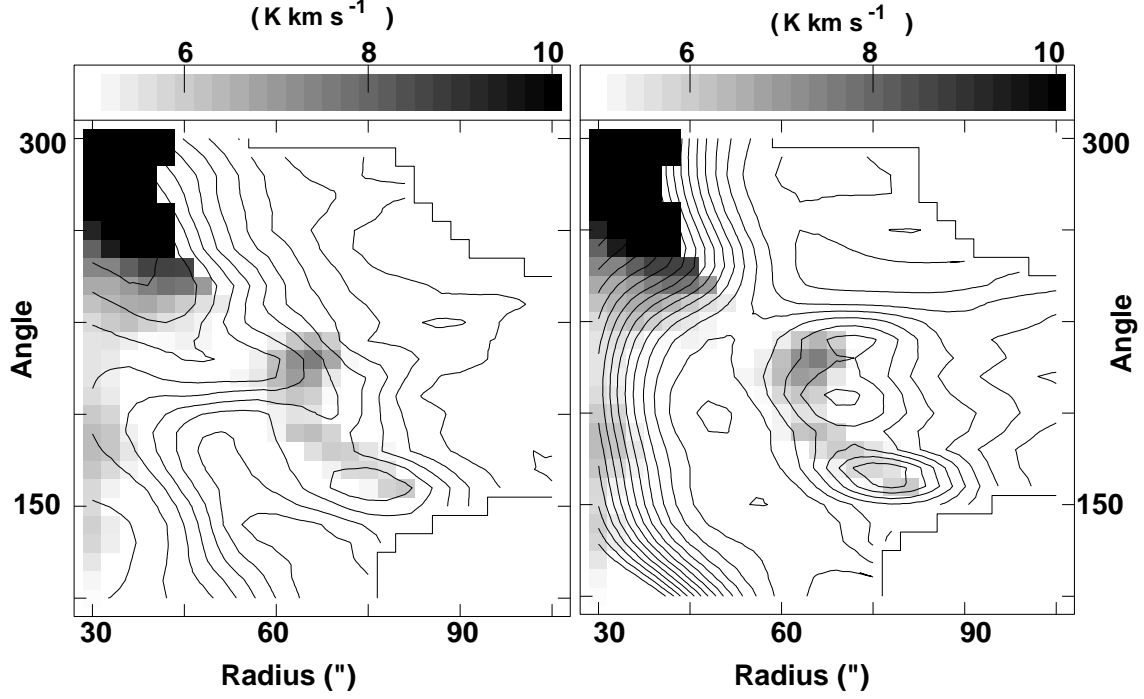


Fig. 4. $R - \theta$ plot of the ^{13}CO intensity (grey scale) from $R = 30''$ to $100''$, superposed on those of (a) ^{12}CO emission and (b) $\text{H}\alpha$ emission (contours), respectively. The inclination angle has been corrected. The contour intervals are the same as figure 3. The units of the horizontal and the vertical axes are arcsec and degree, respectively, and θ is measured counterclockwise from the minor axis. The $\text{H}\alpha$ emission is convolved with the $17''$ beam.

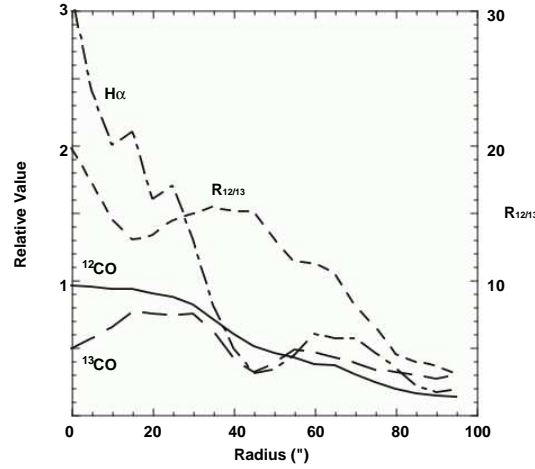


Fig. 5. Radial distributions of the ^{13}CO emission, the ^{12}CO emission, the intensity ratio ($= R_{12/13}$), and the $\text{H}\alpha$ emission. Those of the ^{12}CO and the $\text{H}\alpha$ are based on the same region of the observed one in ^{13}CO .

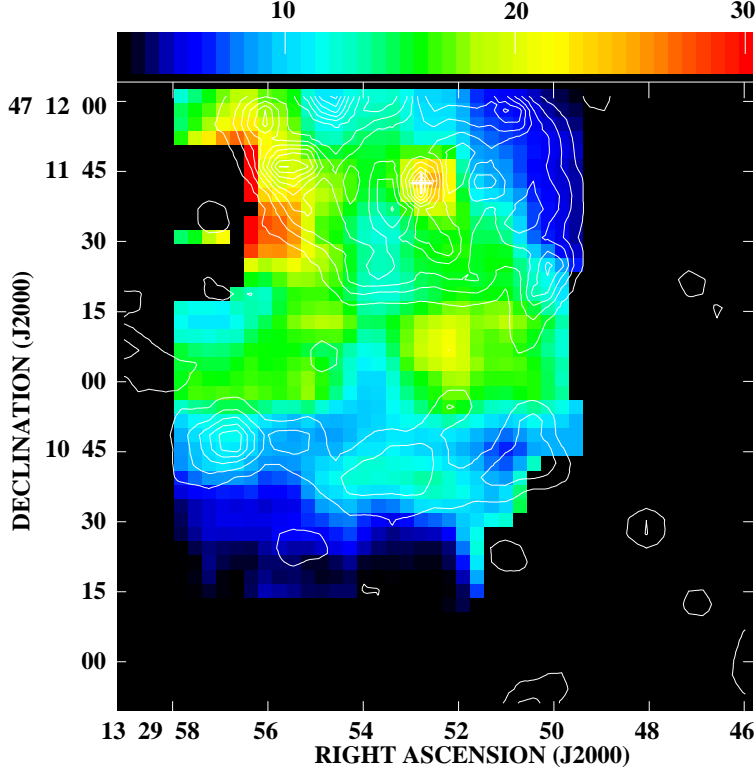


Fig. 6. Map of the intensity ratio ($= R_{12/13}$ color scale) superposed on the $H\alpha$ emission (contour). The cross indicates the galactic center of M 51.

note that the high $R_{12/13}$ regions have an excellent anti-correlation with the $H\alpha$ emission except for the galactic center. In other words, the regions with high $R_{12/13}$ such as the interarm show little or no $H\alpha$ emission, while the low $R_{12/13}$ is seen in the arm region where the $H\alpha$ emission are distributed. However, it must be noted that the figure shows that there is a part of the arm with high $R_{12/13}$ and weak $H\alpha$ emission, which are located at radii from $30''$ to $40''$. We add that there are local peaks on the spiral arm. However, their contrasts have been significantly lower than the arm-interarm contrast. Only the galactic center has both high $R_{12/13}$ and strong $H\alpha$ emission, which is from the AGN of M 51.

We summarize the $R_{12/13}$ in various regions of our Galaxy and galaxies in table 2. A high $R_{12/13}$ has been seen in both IR-bright galaxies (000 [cite]cite.key-Aal95Aalto et al.(1995)) and starburst galaxies (e.g., M 82: 000 [cite]cite.key-Kiku98Kikumoto et al. (1998)), and in diffuse cold clouds, such as high-latitude clouds (000 [cite]cite.key-Knap88Knap & Bowers(1988)). On the other hand, the disk of our Galaxy shows a low $R_{12/13}$ value (000 [cite]cite.key-Sol79Solomon et al.(1979); 000 [cite]cite.key-Pol88Polk et al.(1988)) and the non-active spirals, such as normal and poststarburst galaxies, also have intermediate ratios, ~ 10 , in the disks (e.g., NGC 891: 000 [cite]cite.key-Saka97Sakamoto et al.(1997)). $R_{12/13}$ in these non-active galaxies is lower than those of the starburst galaxies and the high latitude clouds, and higher than that of the disk of our Galaxy. Our results show that the $R_{12/13}$ values in the central region and the interarm

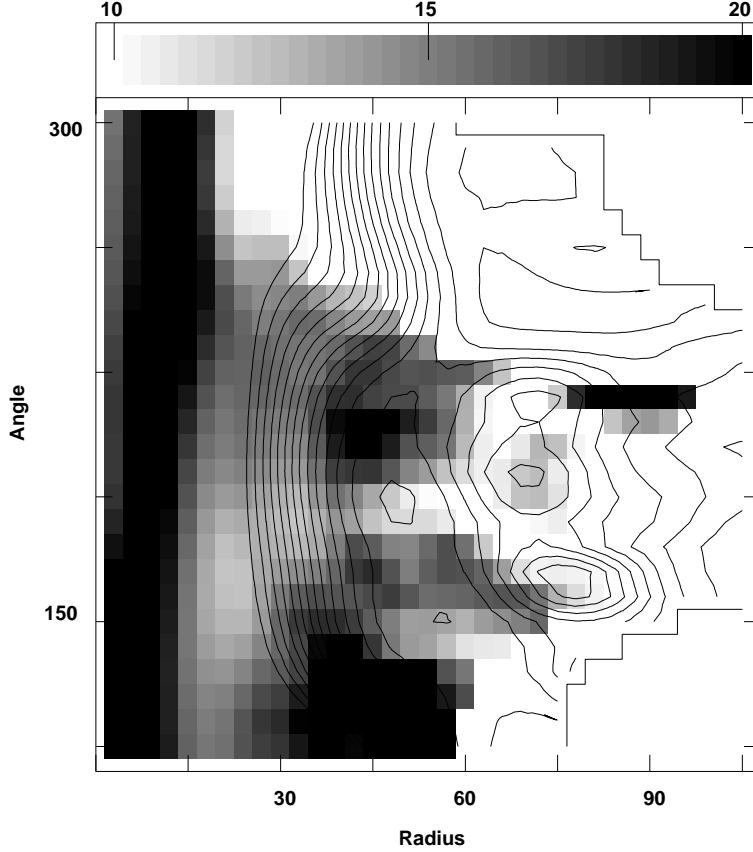


Fig. 7. $R - \theta$ plot of the $R_{12/13}$ (grey scale) superposed on the $H\alpha$ emission (contour). The $H\alpha$ emission is convolved with the $17''$ beam.

of M 51 are higher than that in the spiral arm and are closer to those of starburst galaxies and high-latitude clouds. It is also indicated that in the arm of M 51 the $R_{12/13}$ value is slightly higher than those of non-active galaxies. This is because $R_{12/13}$ measured on the arm of M 51 may include a part of that in the interarm, which has a high $R_{12/13}$ value, due to the narrow arm width ($\sim 10''$), which was obtained by previous interferometric observations with a higher spatial resolution (e.g., 000 [cite]cite.key-Rand90Rand and Kulkarni(1990)). Consequently, it is reasonable to expect that the obtained $R_{12/13}$ on the arm may be higher than that in the arm only, and is possibly similar to that expected from the normal galaxies.

In order to understand the physical properties of the molecular gas in the central and disk regions of M 51 (and also other galaxies) from the ^{12}CO and ^{13}CO data, we used the Large-Velocity-Gradient (LVG) calculations (000 [cite]cite.key-Gol74Goldreich and Kwan (1974); 000 [cite]cite.key-Sco74Scoville & Solomon(1974)) assuming a one-component model. $R_{12/13}$ was calculated as a function of the H_2 number density from 10^1 to 10^6 cm^{-3} , and the kinetic temperature from 10 to 1000 K. The collision rates for CO molecules are available from te[cite]cite.key-Flo85Flower and Launay(1985) ([cite]cite.key-Flo85Flower and Launay(1985)) ($\leq 250 \text{ K}$) and te[cite]cite.key-Mck82McKee et al.(1982) ([cite]cite.key-Mck82McKee et al.(1982)) ($\geq 500 \text{ K}$). We

Table 2. $R_{12/13}$ in galaxies.

galaxy	region	$R_{12/13}$	Remarks
Our Galaxy	Disk	$5.5 - 6.7^{a,b}$	
	High latitude clouds	40^c	
Non-active galaxies			
NGC 891	Center	15.4^d	Edge-on
	Total	6.6^d	
NGC 1808		7.8^e	Hot spot
NGC 4945		$10 - 19^f$	Edge-on
NGC 7331	Center	$6.7 - 8.8^g$	Poststarburst
Active galaxies			
NGC 7479	Bar	$5 - \geq 30^h$	Starburst
M 82	Central region	$20 - \geq 70^i$	Starburst
NGC 4194		20^j	Medium
Arp 299	IC694 nucleus	60^j	Merging
	IC694 disk	10^j	
	NGC3690	13^j	
IR bright galaxies	center	$5 - 35^k$	
M 51	Center	$8 - 9^l$	
		$\geq 20^m$	
	Arm	$9 - 10^l$	
		10^m	
	Interarm	$\geq 15^l$	
		20^m	

a): [te\[cite.key-Sol79Solomon et al.\(1979\)](#) ([\[cite\]cite.key-Sol79Solomon et al.\(1979\)](#)).

b): [te\[cite.key-Pol88Polk et al.\(1988\)](#) ([\[cite\]cite.key-Pol88Polk et al.\(1988\)](#)).

c): [te\[cite.key-Knap88Knap & Bowers\(1988\)](#) ([\[cite\]cite.key-Knap88Knap & Bowers\(1988\)](#)).

d): [te\[cite.key-Saka97Sakamoto et al.\(1997\)](#) ([\[cite\]cite.key-Saka97Sakamoto et al.\(1997\)](#)).

e): [te\[cite.key-Aalt94Aalto et al.\(1994\)](#) ([\[cite\]cite.key-Aalt94Aalto et al.\(1994\)](#)).

f): [te\[cite.key-Berg92Bergman et al.\(1992\)](#) ([\[cite\]cite.key-Berg92Bergman et al.\(1992\)](#)).

g): [te\[cite.key-Isr99Israel and Baas\(1999\)](#) ([\[cite\]cite.key-Isr99Israel and Baas\(1999\)](#)).

h): [te\[cite.key-Hutt00Hüttemeister et al.\(2000\)](#) ([\[cite\]cite.key-Hutt00Hüttemeister et al.\(2000\)](#)).

i): [te\[cite.key-Kiku98Kikumoto et al. \(1998\)](#) ([\[cite\]cite.key-Kiku98Kikumoto et al. \(1998\)](#)).

j): [te\[cite.key-Aal97Aalto et al.\(1997\)](#) ([\[cite\]cite.key-Aal97Aalto et al.\(1997\)](#)).

k): [te\[cite.key-Aal95Aalto et al.\(1995\)](#) ([\[cite\]cite.key-Aal95Aalto et al.\(1995\)](#)).

l): [te\[cite.key-GB93aGarcia-Burillo et al.\(1993a\)\(1993a\)](#).

m): This work

fixed the molecular abundances to the ‘standard’ relative abundance as $Z(^{13}\text{CO}) = [^{13}\text{CO}]/[\text{H}_2] = 1 \times 10^{-6}$ (000 [cite]cite.key-Sol79Solomon et al.(1979)) and $[^{12}\text{CO}]/[^{13}\text{CO}] = 50$. We also fixed the velocity gradient, dv/dr , as a general value of $1.0 \text{ km s}^{-1}\text{pc}^{-1}$. The calculated results are shown in figure 8 (000 [cite]cite.key-Matsu00Matsushita(2000)). This diagram indicates that $R_{12/13}$ depends mainly on density when the temperature is not high ($<100 \text{ K}$). In the Galactic disk, the temperature of typical molecular clouds has a typical value of 10 K . In this case, it seems reasonable that $R_{12/13}$ is a good tracer for density of molecular clouds, namely $R_{12/13}$ decreases with the density. Our results show that a low $R_{12/13}$ value, smaller than 10, is seen in the arm associated with the $\text{H}\alpha$ emission, and the interarm and a part of the arm with no associated $\text{H}\alpha$ emission have a high $R_{12/13}$ value of ~ 20 , as mentioned above. This figure indicates that there are diffuse molecular clouds with a density of $2 \times 10^2 \text{ cm}^{-3}$ in the interarm and the arm with no associated $\text{H}\alpha$ emission, whereas most molecular clouds in the arm associated with the $\text{H}\alpha$ emission have a density larger by a factor of two, in the case that the same temperatures of molecular clouds in each region, e.g., 10 K , is assumed. Namely, the massive star-forming regions traced by the $\text{H}\alpha$ emission are located in the denser clouds with a low $R_{12/13}$ value.

On the other hand, the galactic center as well as the interarm region also has a high $R_{12/13}$ value of ≥ 20 , which is not consistent with the results obtained by te[cite]cite.key-GB93aGarcia-Burillo et al.(1993a)(1993a). The reason for this may be the difference in the spatial resolution between their ($23''$) and our ($17''$) observations. Since our $R_{12/13}$ map shows a very low ratio in the bar-end/beginning of the spiral arm, the larger beam can cause contamination with this low-ratio region. To confirm this, we convolved our maps to their resolution and measured the ratio at the center. The measured ratio is $12 - 13$, which is in agreement with their value ($8 - 9$) within the errors. As a result, it is reasonable to expect that $R_{12/13}$ decreases in their study.

Figure 8 shows that the high $R_{12/13}$ values at the central region of M 51 suggests two possibilities for the physical condition of molecular gas: one is a low-density ($\sim 10^2 \text{ cm}^{-3}$) condition; the other is a high-density ($10^{4\pm1} \text{ cm}^{-3}$) and high temperature ($\geq 300 \text{ K}$) condition. To define the physical conditions of the molecular gas at the center, we compared our results with the previously published high resolution observations. The distribution of molecular gas at the central region of M 51 is strongly concentrated toward the center; interferometric ^{12}CO (000 [cite]cite.key-Saka98Sakamoto et al.(1998); 000 [cite]cite.key-Aal99Aalto et al.(1999)) and HCN (000 [cite]cite.key-Kohno96Kohno et al.(1996)) observations clearly show a centrally peaked distribution, and suggest disk-like kinematics surrounding the low-luminosity AGN (see also 000 [cite]cite.key-Sco98Scoville et al.(1998)). On the other hand, the high-resolution ^{13}CO observations display a lack of ^{13}CO emission toward the center (000 [cite]cite.key-Matsu98Matsushita et al.(1998)). The $\text{HCN}/^{12}\text{CO}$ intensity ratio suggests that the central region is rich in dense molecular gas with a density of $\sim 10^{4-5} \text{ cm}^{-3}$ (000 [cite]cite.key-Kohno96Kohno et al.(1996)). The $\text{HCN}/^{13}\text{CO}$ ratio shows a high value (> 3) and suggests that the central region is domi-

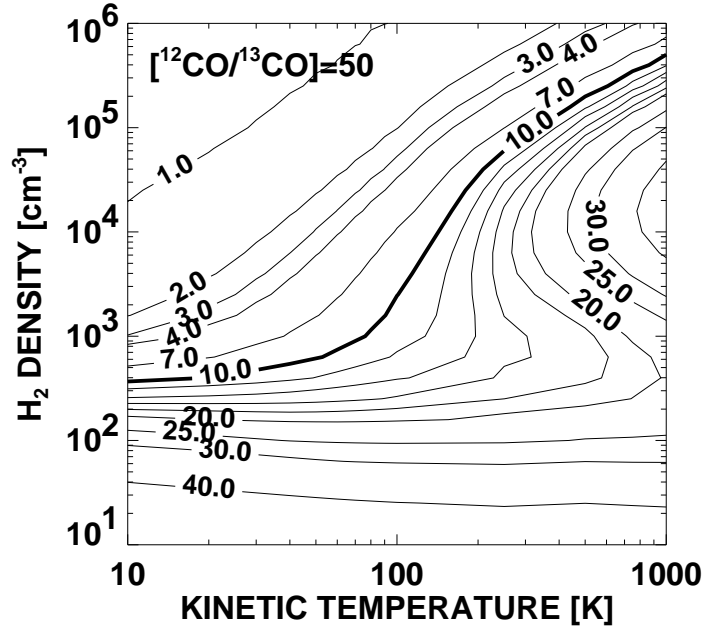


Fig. 8. Density (vertical axis) and temperature (horizontal axis) dependence of the $^{12}\text{CO}/^{13}\text{CO}$ intensity ratio ($= R_{12/13}$; 000 [cite]cite.key-Matsu00Matsushita(2000)). The solid contours show curves of constant $R_{12/13}$, and the thick solid curve indicates $R_{12/13}$ of 10.0.

nated by hot (≥ 100 K) and dense ($\sim 10^{5\pm1} \text{ cm}^{-3}$) gas (000 [cite]cite.key-Matsu98Matsushita et al.(1998)), and may be correlated with the AGN (000 [cite]cite.key-Matsu99Matsushita et al.(1999)). If our observations are to be consistent with previous ones, and if the density is roughly 10^5 cm^{-3} , then our value of $R_{12/13}$ (20) implies a temperature of several hundred K. Active galaxies, such as starbursts, also have high $R_{12/13}$ values as mentioned above, which may also be due to the molecular clouds with high density and high temperature. We can say that the central region of M 51 has hot, dense clouds as do active galaxies.

3.3. Kinematics

Figure 9a shows the velocity field of the ^{13}CO emission, which was made by tracing the peak velocity of the ^{13}CO line profile. The previous observations of H I, ^{12}CO and H α emissions for the large area provide a position angle of M 51 of 170° (000 [cite]cite.key-Tully74Tully(1974)). In the central region of figure 9a, we found a feature difference from that expected from the position angle, P.A. = 170° , namely isovelocity contours show a tilt from the minor axis of the galaxy. It is reported from near-infrared observations that there is an oval potential in the central region of M 51 (000 [cite]cite.key-Pie86Pierce(1986); 000 [cite]cite.key-TG88Thronson and Greenhouse(1988)). An oval potential causes a distortion of the velocity field; this feature in M 51 was found in previous observations (e.g., 000 [cite]cite.key-Kuno97Kuno & Nakai(1997)).

The isovelocity contours also show S-shape disturbances from pure rotation at the spiral arm. This is consistent with previous studies of ^{12}CO . This could be due to streaming motion caused by a density wave, as was already suggested based on previous studies with ^{12}CO observations (000 [cite]cite.key-GB93aGarcia-Burillo et al.(1993a)a; 000 [cite]cite.key-Kuno97Kuno & Nakai(1997)).

Because the observations give only the velocity component in the line of sight directly, we present a Position–Velocity (P–V) diagram along the major axis (P.A. = 170°) to indicate the tangential velocity (figure 9b). The width of the strip used to make the P–V diagram along the major axis is $17''$. We find that there is a central depression and a concentration at the end of the rigid rotation ($R \sim 20''$) in figure 9b. We can also see a velocity shift of 15 km s^{-1} at the position of the spiral arm indicated by arrow in the figure. These correspond to $\sim 40 - 50 \text{ km s}^{-1}$ on the plane of the galaxy. This was pointed out by previous ^{12}CO observations (000 [cite]cite.key-Kuno97Kuno & Nakai(1997); 000 [cite]cite.key-Aal99Aalto et al.(1999)), and it was suggested that molecular gas is shocked across the spiral arm. This figure suggests that the dense gas which is traced by ^{13}CO as well as diffuse gas traced by ^{12}CO is shocked by the density wave.

3.4. *Time Delay of Dense Gas Formation and Star Formation*

As mentioned in section 3.2, the ^{13}CO emission shows good agreement with the $\text{H}\alpha$ emission rather than with the ^{12}CO one, except for in a part of the arms, and they are located on the downstream side of the ^{12}CO . Here, we discuss the effect of the spiral arms, namely the density wave on the dense gas and the star-formation mechanism. Before turning to this problem, we must consider the exceptional $\text{H}\alpha$ emission region, which shows an offset from the ^{13}CO emission.

Because this region is far from the dust lane and the ^{12}CO arm, as mentioned in subsection 3.1.2, it seems reasonable to expect that it has escaped from the spiral arm. If the star formation is triggered by a shock originating from the density wave, it indicates that this region is an “older, or a more evolved star forming region” than those on the spiral arm, since the location of the shock is supposed to be the dust lane. We may say that, in the evolved star-forming region, the dense gas decreases due to consumption by the star formation, the ionization, the photo-dissociation and so on, and the dense gas formation, itself, is suppressed because of a decrease in the surrounding gas when it is far from the arm. For this reason, it seems reasonable that the above $\text{H}\alpha$ emission region has no associated dense gas which is traced by ^{13}CO . Therefore, when we consider the effect of the density wave on the formation mechanism of the dense gas and the following star, it should be an exception.

In order to investigate the effect of a spiral arm on the nature of molecular gas, we present the azimuthal distributions of ^{12}CO , ^{13}CO , $R_{12/13}$, and $\text{H}\alpha$ at radii of $30''$ and $45''$ (figure 10). Although it indicates that the ^{12}CO and ^{13}CO emissions increase toward the spiral arm from

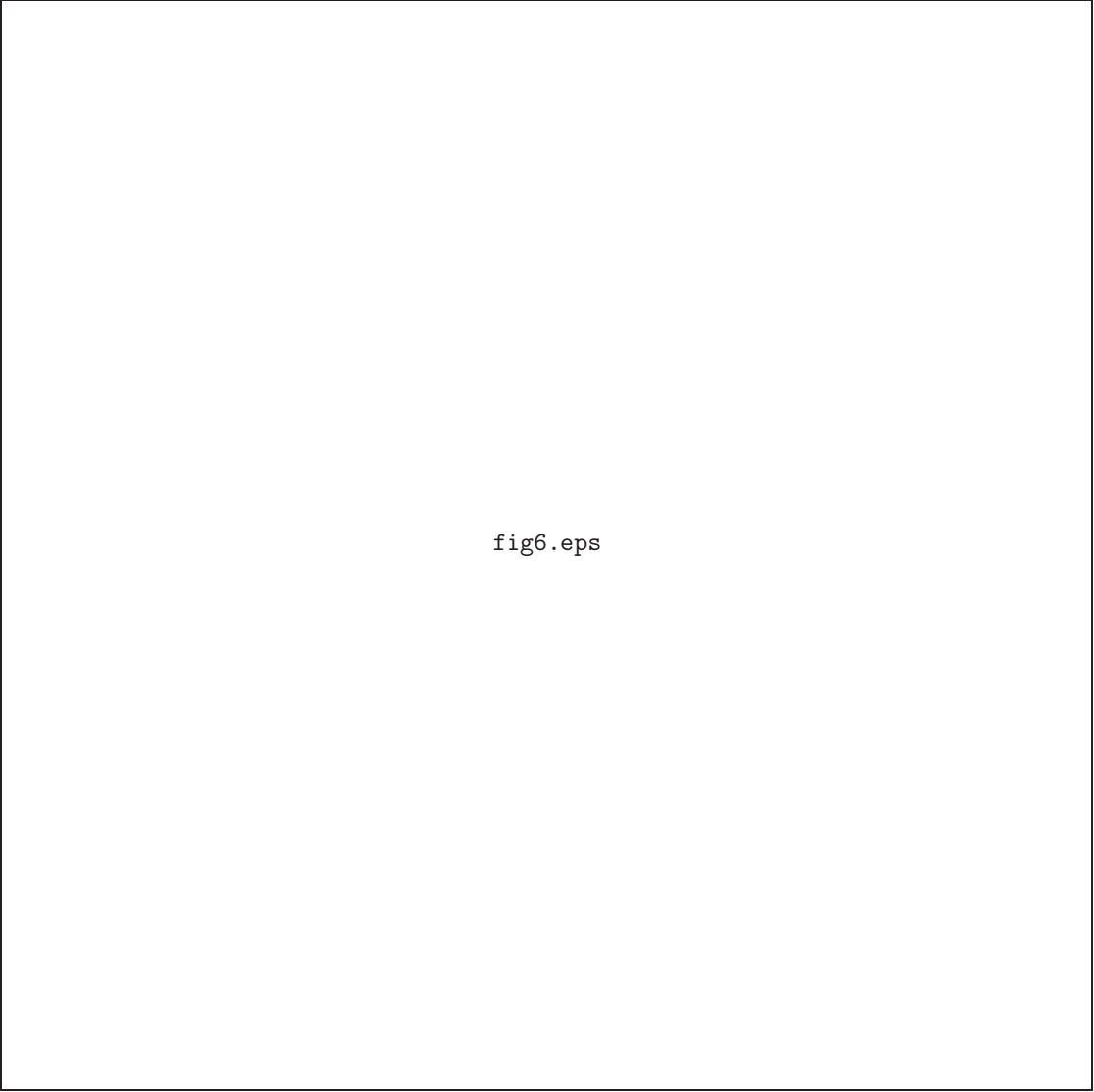


fig6.eps

Fig. 9. (a) Velocity field. The contour interval is 10 km s^{-1} and the thick line indicates 460 km s^{-1} . The dashed lines indicate the major and minor axes. (b) P-V diagrams along major axis. The arrow indicates the location of the arm. The contour interval is 15 mK and the lowest contour is the 30 mK .

the interarm, their peaks are not coincident, namely, the rise of the ^{13}CO is delayed compared with that of the ^{12}CO . As a result, $R_{12/13}$ also shows a decrease across the spiral arm and the trend mentioned above is confirmed. The delays are 10 – 20 deg at radii from 30'' to 50'' and are smaller at larger radii. This suggests that there is a time delay of the formation of dense gas traced by ^{13}CO from the accumulation of molecular gas by the density wave. The small delay (in the unit of degree) at a large radius is reasonable, if there is the same time delay between the gas accumulation caused by the density wave and the dense gas formation. The difference, d , is 400 – 800 pc at a radius of 48'', corresponding to 2.2 kpc. We can estimate the time delay corresponding to d from the rotation curve. This time delay is given by $\tau_d = d/V_{\text{arm}}$, where V_{arm} is the velocity perpendicular to the arm in the frame corotating with the spiral pattern. For the adopted pattern speed of $\Omega_p = 14 \text{ km s}^{-1} \text{ kpc}^{-1}$ (see 000 [cite]cite.key-Kuno95Kuno et al.(1995)) and the pitch angle of 20 degrees, we can obtain the value of $V_{\text{arm}} = 58 \text{ km s}^{-1}$. This is the upper limit of the V_{arm} because we assume a circular motion. Then the corresponding time delay is $\tau = (0.7 - 1.5) \times 10^7 \text{ yr}$ at 2.2 kpc.

We must note that the estimated time delay depends on the adopted pattern speed. That is, if a larger pattern speed is adopted, V_{arm} becomes small and τ becomes large. Actually, the pattern speed obtained by previous studies also has a result of $27 \text{ km s}^{-1} \text{ kpc}^{-1}$ (000 [cite]cite.key-GB93bGarcia-Burillo et al.(1993b)b), and may be larger. In the case of larger pattern speed, the above estimate of the time delay is the lower limit. We add that τ does not increase 1.2 times even if the pattern speed doubles.

It has been known that the $\text{H}\alpha$ emission, indicating massive star formation, is also located on the downstream side of the ^{12}CO emission (000 [cite]cite.key-Vog88Vogel et al.(1988); 000 [cite]cite.key-Rand92Rand et al.(1992)). As noted above, it shows good correspondence of the ^{13}CO with the $\text{H}\alpha$ in the disk of M 51. From these results, we presume that the star formation occurred following dense gas formation later than $\sim 10^7 \text{ yr}$ after the accumulation of diffuse molecular gas caused by density wave.

Here, in order to address the origin of the delay of the dense gas and the star formation from the compression of the gas due to the density wave, we consider the gravitational instability of molecular gas in the spiral arm. Here, we can introduce the Toomre Q parameter to estimate the effect of gravitational instability on the mechanism for dense gas formation (e.g. 000 [cite]cite.key-Ken89Kennicutt(1989)). The previous studies suggest that the Q parameters have a correlation with the star-formation activity (000 [cite]cite.key-Kohno01Kohno et al.(2001); 000 [cite]cite.key-Shio98Shioya et al.(1998); 000 [cite]cite.key-Tosa97Tosaki and Shioya(1997); 000 [cite]cite.key-Ken89Kennicutt(1989)). The Q parameter is expressed as $Q = \Sigma_{\text{crit}}/\Sigma_{\text{gas}}$, where Σ_{gas} is the gas surface density and Σ_{crit} is critical density for gravitational instabilities, and is used as a criteria for local instability in an isothermal thin disk. Σ_{crit} is given by

$$\Sigma_{\text{crit}} = \alpha \frac{\sigma_v \kappa}{\pi G} = 74\alpha \left(\frac{\sigma_v}{\text{km s}^{-1}} \right) \left(\frac{\kappa}{\text{km s}^{-1} \text{ pc}^{-1}} \right) M_{\odot} \text{ pc}^{-2}, \quad (1)$$

where σ_v and κ are the velocity dispersion and the epicyclic frequency for the gas disk, respectively. α is a dimensionless constant (000 [cite]cite.key-Toom64Toomre(1964)). κ is expressed as

$$\kappa = \left\{ 2 \frac{V(r)}{r} \left[\frac{V(r)}{r} + \frac{dV(r)}{dr} \right] \right\}^{0.5} \quad (2)$$

where $V(r)$ is rotational velocity at the radius of r . In the case that we use 10 km s^{-1} as the velocity dispersion and 0.63 as α (000 [cite]cite.key-Ken89Kennicutt(1989)), we obtain a Σ_{crit} of $84 M_{\odot} \text{pc}^{-2}$ and $55 M_{\odot} \text{pc}^{-2}$ at the radii of $30''$ and $50''$, respectively. It should be added that we have used the observational rotation curve, which was fitted with the potential model of [cite]cite.key-Miya75Miyamoto & Nagai(1975) ([cite]cite.key-Miya75Miyamoto & Nagai(1975)), as the rotational velocity and the gradient (see 000 [cite]cite.key-Kuno97Kuno & Nakai(1997)). Because the surface density of the gas at the spiral arm is $\sim 200 M_{\odot} \text{pc}^{-2}$ (000 [cite]cite.key-Kuno95Kuno et al.(1995)), the Q values are 0.4 and 0.3. This indicates that the gas in the arm is gravitationally unstable. Therefore, dense gas formation in the arm may occur via a gravitational instability of the gas; consequently the star formation occurs there.

Next, we compare the above time scale with those of gravitational instabilities. The growth time for a gravitational instability can be estimated as follows (e.g., 000 [cite]cite.key-Lar87Larson (1987)):

$$\tau = \frac{\sigma_v}{\pi G \Sigma_{\text{gas}}}, \quad (3)$$

where σ_v and Σ_{gas} are the velocity dispersion and the average surface density of gas, respectively. We can adopt these values at a radius of $40''$ as 10 km s^{-1} and $200 M_{\odot} \text{pc}^{-2}$, respectively, from the peak of the ^{12}CO arm (000 [cite]cite.key-Kuno95Kuno et al.(1995)). The estimated timescale is $\sim 10^7$ years, which is similar to the above time delay between the ^{12}CO and the ^{13}CO , and we can explain the mechanism of dense gas formation by the gravitational instability.

We must note that an offset between the ^{12}CO and the HCN has been found in the central region of NGC6951 (000 [cite]cite.key-Kohno99Kohno et al.(1999)), which corresponds to $\sim 10^6$ yr. HCN is a tracer of dense gas with a density of 10^{4-5} cm^{-3} , which is higher than ^{13}CO . This value is also similar to the timescale of gravitational instabilities. It seems reasonable to suppose that dense gas formation occurs after $\sim 10^{6-7}$ yr from the accumulation of gas. As a result, star formation also occurs after that. It is likely that gravitational instability plays an important role in the mechanism of dense gas and star formation.

4. Conclusions

We present the results of $^{13}\text{CO}(J = 1-0)$ mapping observations toward the southern bright arm region of nearby spiral galaxy M 51 carried out with the Nobeyama 45 m telescope. The main conclusions are summarized as follows:

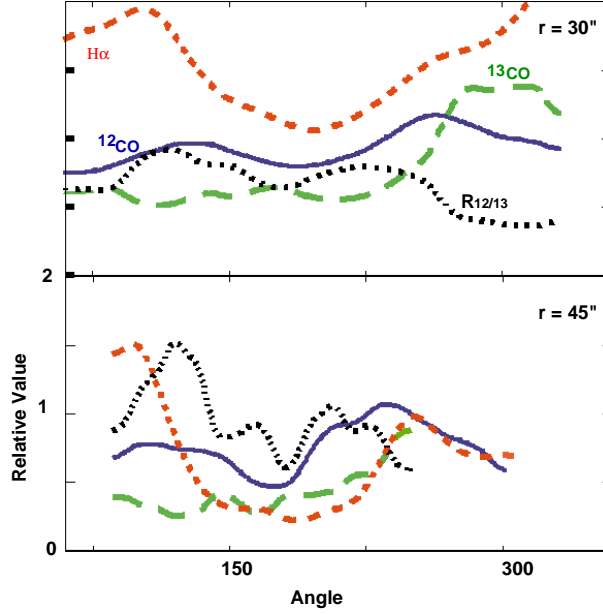


Fig. 10. Azimuthal distributions of the ^{13}CO emission, the ^{12}CO emission and the intensity ratio obtained with NRO-45m, and the $\text{H}\alpha$ emission convolved to the $17''$ beam at radii of $30''$ and $45''$. The horizontal and vertical axes of each panel are the azimuthal angles (in degree) and their relative values, respectively. The gas flows from left to right in this figure.

1. We find a depression of the ^{13}CO emission in the central $20'' - 30''$ region, corresponding to ~ 1 kpc. There is a ring-like structure surrounding the central region, which corresponds to the bar-end or the beginning of the spiral arm.

2. The arm structure in the ^{13}CO is shown in the total integrated intensity map, and the arm-to-interarm ratio is 2 – 4. The ratio of the ^{13}CO in the observed region is higher than that of the ^{12}CO . Although it shows a global correspondence with the ^{12}CO , a detailed comparison shows spatial differences between them, e.g., there is a depression of the ^{13}CO on the spiral arm.

3. The ^{13}CO distribution shows a good correspondence with that of the $\text{H}\alpha$ emission, except for in the galactic center, rather than the ^{12}CO . The ^{13}CO and the $\text{H}\alpha$ show the depression at the same position on the spiral arm and are located on the downstream side of the ^{12}CO .

4. A velocity shift is detected at the position of the spiral arm, which suggests a streaming motion caused by the density wave.

5. The $^{12}\text{CO}/^{13}\text{CO}$ ratio has a range from 4 to ≥ 20 . The central region and the interarm indicate a high value of ~ 20 , while a low value of ~ 10 is shown in the arm. They indicate that there is denser gas in the arm than in the interarm. The densities in the arm and the interarm regions were derived to be $\geq 6 \times 10^2$ and $2 \times 10^2 \text{ cm}^{-3}$, respectively, based on the LVG calculation. The high ratio in the central region is due to very hot and dense gas related to

AGN in the nucleus of M 51.

6. The azimuthal distribution at a constant radius shows that the ^{13}CO emissions are located on the downstream side of the ^{12}CO emission. This indicates that there is a time delay from the accumulation of gas caused by shock to the dense gas formation, and the resultant star formation. This time delay leads to $\sim 10^7$ yr from the galactic rotation. This timescale is similar to the growth time for the gravitational instability. It suggests that gravitational instability plays an important role in dense gas formation.

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References

- [Aalto et al.(1999)] Aalto, S., Hüttemeister, S., Scoville, N. Z., & Thaddeus, P. 1999, ApJ, 522, 165
- [Aalto et al.(1997)] Aalto, S., Radford, S. J. E., Scoville, N. Z., & Sargent, A. I. 1997, ApJ, 475, L107
- [Aalto et al.(1995)] Aalto, S., Booth, R. S., Black, J. H., & Johansson, L.E.B. 1995, A&A, 300, 369
- [Aalto et al.(1994)] Aalto, S., Booth, R. S., Black, J. H., Koribalski, B., & Wielebinski, R. 1994, A&A, 286, 365
- [Bergman et al.(1992)] Bergman, P., Aalto, S., Black, J. H., & Rydbeck, G. 1992, A&A, 265, 403
- [de Vaucouleurs et al.(1991)] de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Jr., Buta, R. J., Paturel, G., & Fougu  , P. 1991, Third Reference Catalogue of Bright Galaxies (New York: Springer-Verlag)
- [Flower and Launay(1985)] Flower, D. R., & Launay, J. M. 1985, MNRAS, 214, 271
- [Garcia-Burillo et al.(1993a)] Garcia-Burillo, S., Combes, F., & Gerin, M. 1993a, A&A, 274, 148
- [Garcia-Burillo et al.(1993b)] Garcia-Burillo, S., Guelin, M., & Cernicharo, J. 1993b, A&A, 274, 123
- [Goldreich and Kwan (1974)] Goldreich, P., & Kwan, J. 1974, ApJ, 189, 441
- [Elmegreen et al.(1989)] Elmegreen, B. G., Seiden, P., & Elmegreen, D. M. 1989, ApJ, 343, 602
- [Ho et al.(1995)] Ho, L. C., Filippenko, A. V., & Sargent, W. L. 1995, ApJS, 98, 477
- [H  ttemeister et al.(2000)] H  ttemeister, S., Aalto, S., Das, M., & Wall, W. F. 2000, A&A, 363, 93
- [Israel and Baas(1999)] Israel, F. P., & Baas, F. 1999, A&A, 351, 10
- [Kennicutt(1989)] Kennicutt, R. C. Jr. 1989, ApJ, 344, 685
- [Kennicutt et al.(1989)] Kennicutt, R. C. Jr., Edgar, B. K., & Hodge, P. W. 1989, ApJ, 337, 761
- [Kikumoto et al. (1998)] Kikumoto, T., Taniguchi, Y., Nakai, N., Ishizuki, S., Matsushita, S., & Kawabe R. 1998, PASJ, 50, 309
- [Knap & Bowers(1988)] Knapp, G. R., & Bowers, P. F. 1988, ApJ, 331, 974
- [Kohno et al.(2001)] Kohno, K., Tosaki, T., Matsushita, S., Vila-Vilaro, B., & Kawabe, R. 2001,

submitted to PASJ

- [Kohno et al.(1999)] Kohno, K., Kawabe, R., & Vila-Vilaro, B. 1999, ApJ, 511, 157
- [Kohno et al.(1996)] Kohno, K., Kawabe, R., Tosaki, T., & Okumura S. K. 1996, ApJ, 461, L29
- [Kuno & Nakai(1997)] Kuno, N., & Nakai, N. 1997, PASJ, 49, 279
- [Kuno et al.(1995)] Kuno, N., Nakai, N., Handa, T., & Sofue, Y. 1995, PASJ, 47, 745
- [Larson (1987)] Larson, R. B., 1987, Starburst and Galaxy Evolution, ed. T. X. Thuan, T. Montmerle, & J. Tran Thann Van (Gif-sur-Yvette: Editions Frontières), 467
- [Matsushita et al.(1998)] Matsushita, S., Kohno, K., Vila-Vilaro, B., Tosaki, T., & Kawabe, R. 1998, ApJ, 495, 267
- [Matsushita et al.(1999)] Matsushita, S., Kohno, K., Vila-Vilaro, B., Tosaki T., & Kawabe, R. 1999, Adv. Sp. Res., 23, 1015
- [Matsushita(2000)] Matsushita, S. 2000, Ph.D. Thesis, The Graduate University for Advanced Studies
- [McKee et al.(1982)] McKee, C. F., Storey, J. W. V., Watson, D. W., & Green, S. 1982, ApJ, 259, 647
- [Miyamoto & Nagai(1975)] Miyamoto, M., & Nagai, R. 1975 PASJ, 27, 533
- [Nakai et al.(1994)] Nakai, N., Kuno, N., Handa, T., & Sofue, Y., 1994, PASJ, 46, 527
- [Pierce(1986)] Pierce, M. J. 1986, AJ, 92, 285
- [Polk et al.(1988)] Polk, K. S., Knapp, G. R., Stark, A. A., & Wilson, R. W. 1988, ApJ, 332, 432
- [Rand(1993)] Rand, R. J. 1993, ApJ, 410, 68
- [Rand et al.(1992)] Rand, R. J., Kulkarni, S. R., & Rice W. 1992, ApJ, 390, 66
- [Rand and Kulkarni(1990)] Rand, R. J., & Kulkarni, S. R. 1990, ApJ, 349, L43
- [Sakamoto et al.(1998)] Sakamoto, K., Okumura, S. K., Ishizuki, S., & Scoville, N. Z. 1998, ApJS, 124, 403
- [Sakamoto et al.(1997)] Sakamoto, S., Handa, T., Sofue, Y., Honma, M., & Sorai, K. 1997, ApJ, 475, 134
- [Sandage and Tammann(1974)] Sandage, A., & Tammann, G. A. 1974, ApJ, 194, 559
- [Scoville et al.(1998)] Scoville, N. Z., Yun, M. S., Armus, L., & Ford, H. 1998, ApJ, 493, L63
- [Scoville & Solomon(1974)] Scoville, N. Z., & Solomon, P.M. 1974, ApJ, 187, L67
- [Shioya et al.(1998)] Shioya, Y., Tosaki, T., Ohyama, Y., Murayama, T., Yamada, T., Ishizuki, S., & Taniguchi, Y. 1998, PASJ, 50, 317
- [Solomon et al.(1979)] Solomon, P. M., Sanders, D. B., Scoville, N. Z. 1979, ApJ, 232, L89
- [Sunada et al.(1995)] Sunada, K., Noguchi, T., Tsuboi, M., & Inatani, J. 1995, in ASP Conf. Ser. 75; Multi-feed Systems for Radio Telescopes, ed. D. T. Emerson, & J. M. Payne, 230 (San Francisco: ASP)
- [Terashima et al.(1998)] Terashima, Y., Ptak, A., Fujimoto, R., Itoh, M., Kunieda, H., Makishima, K. & Serlemitsos, P. J., 1998, ApJ, 496, 210
- [Thilker et al.(2000)] Thilker, D. A., Braun, R., & Walterbos, R. A. M. 2000, AJ, 120, 3070
- [Thronson and Greenhouse(1988)] Thronson, H. A. Jr., & Greenhouse, M. A. 1988, ApJ, 327, 671.
- [Toomre(1964)] Toomre, A. 1964, ApJ, 139, 1217
- [Tosaki and Shioya(1997)] Tosaki, T., & Shioya, Y. 1997, ApJ, 484, 664
- [Tully(1974)] Tully, R.B. 1974, ApJS, 27, 449
- [Turner and Ho(1994)] Turner, J. L., & Ho, P. T. P. 1994, ApJ, 421, 122

[Vogel et al.(1988)] Vogel, S. N., Kulkarni, S. R., & Scoville, N. Z. 1988, *Nature*, 334, 402

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